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Electronic THz-spectrometer for plasmonic enhanced deep subwavelength layer detection

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Abstract — We demonstrate the operation of a miniaturized all-electronic CMOS based THz spectrometer with performances comparable to that of a THz-TDS spectrometer in the frequency range 20 to 220 GHz. The use of this all-electronic THz spectrometer for detection of a thin TiO_2 layer and a *B. subtilis* bacteria film on top of a plasmonic surface is evaluated. The detection of deeply subwavelength layers with comparable performance as a femtosecond laser based THz-TDS spectrometer is demonstrated. The size of the all-electronic spectrometer is 5 cm by 1cm. The high degree of integration of this spectrometer in combination with plasmonics enhanced sensitivity opens the way to bring THz spectroscopy to consumer applications or to the practitioner's office.

Index Terms — Terahertz spectroscopy, plasmonics, sensing, CMOS non-linear transmission line.

I. INTRODUCTION

Terahertz spectroscopy has recently attracted a large interest owing to the promising prospects for the identification of substances such as pharmaceuticals, explosives or gases. Most of the terahertz spectrometers are based on the time domain spectroscopy method (THz-TDS) and rely on THz generation from a photoconductive antenna or a non-linear crystal illuminated by femtosecond laser pulses. Therefore THz-TDS spectrometers are intrinsically large setups. Such equipment is mostly confined to the laboratory environment. Applications in a consumer's context require a compact, low cost, low drive power device with sufficient output power.

Recently, several miniaturized THz transmitters and receivers based on CMOS and BiCMOS technology have been presented by different groups [1-3]. However the spectral range of these systems is limited to one or several narrow frequency bands and a continuous tuning over broad frequency ranges is not possible. For a general purpose spectrometer, the required frequency and bandwidth depends on the application and frequency tuning to detect narrow-band spectral features is essential. In contrast to [1-3], the miniaturized THz spectrometer used in this study [4, 5] allows full coverage of broad terahertz frequency bands due to the use of nonlinear transmission lines (NLTL). It is built in conventional CMOS and 3D chip-scale packaging (3D-CSP) technology. The device is composed of a transmitter *and* a receiver, can work in a frequency range from 6 GHz to 220 GHz and allows both transmission and reflection measurement configurations.

Recently detection of thin layers of fungi and bacteria was demonstrated using terahertz metamaterials on a silicon carrier substrate [6]. Furthermore, sensitivity enhancement for thin layer detection using plasmonic substrates was shown in [7-9]. In all these experiments, a large THz-TDS setup was used to generate and detect the terahertz signal passing through the sample. To make this technology available outside the laboratory environment, miniaturization of the terahertz source and receiver is required with competitive sensitivity over broad frequency ranges. In this paper we present a miniaturized broadband all-electronic terahertz spectrometer and compare its performance to a conventional THz-TDS setup based on ultrafast optics. This comparison is done in terms of the sensitivity to detect ultra-thin dielectric layers of inorganic or biological nature. Both THz spectrometers are used in combination with plasmonic structures for sensitivity enhancement. We demonstrate that the sensing performances of both instruments are comparable, hence bringing broadband THz spectroscopy and sensing to a broad range of out-of-the-lab applications. In the following sections, we give a comparison of both setups and a comparison of measurements to detect thin inorganic and biological layers.

II. COMPARISON OF THE TWO SPECTROMETERS

The integrated THz spectrometer is an all-electronic device based on CMOS technology [4, 5]. Fig. 1 top presents a schematic drawing of the spectrometer consisting of a hybrid transmitter (Tx) and receiver (Rx) module, each composed of a CMOS chip and a Vivaldi antenna in 3D-CSP technology. The operation of both Tx and Rx parts is based on progressively reshaping a 20 GHz input signal into a signal with increased higher harmonics content with a CMOS non-linear transmission line (NLTL). The device used here has detectable

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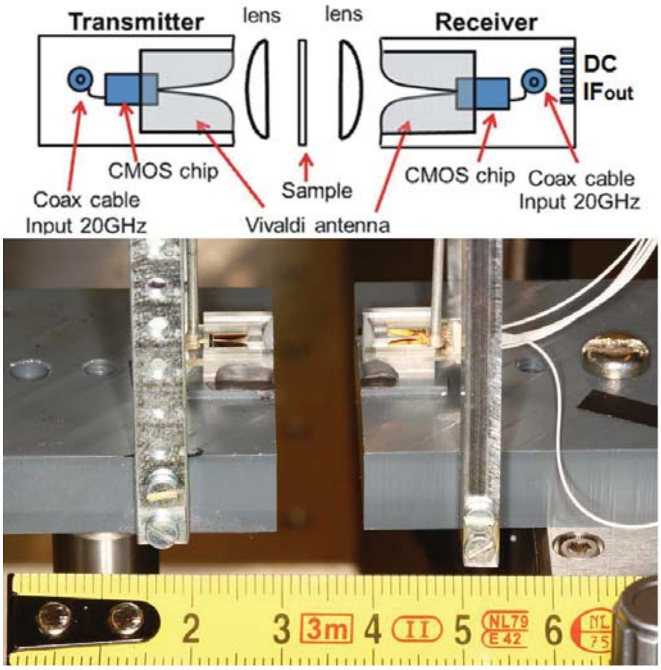

Fig. 1. Schematic and photograph (without sample) of the all-electronic THz-spectrometer setup.

harmonics at least until 280 GHz. Hybrid broad band Vivaldi antennas in Tx and Rx are facing miniaturized Teflon lenses to transmit and collect the signals. In the transmission configuration, the THz beam shaped by the Vivaldi antenna and the lens, is emitted towards the sample.

The transmitted beam is collected by the receiver module, which down-converts the broadband signal in a fast Schottky diode based sampling bridge into a signal with harmonics from 1.2 to 16.8 MHz, measured with a spectrum analyzer. Fig. 1 bottom displays a photograph of the setup excluding the two frequency generators and the spectrum analyzer used to drive the THz device and measure the down converted signal. The footprint of the set-up is in the order of 5 cm by 1cm. The 20 GHz signal source and the spectrum analyzer (used only up to 16.8 MHz) can be integrated on the same CMOS chip of the THz devices. The all-electronic THz spectrometer is therefore compact and portable. Moreover, the power levels needed for the operation of the device are in the range of few watts – making the device suitable for many consumer applications. Fig. 2 shows a schematic of the THz-TDS conventional spectrometer, used as reference for this study. The footprint is in the order of 1 m. Terahertz time-domain spectroscopy consists in measuring the transmission of single-cycle, picosecond THz pulses through a sample under investigation. This technique measures the electric field amplitude as a function of time. It provides information both on the amplitude and the phase of the electromagnetic field, and allows for picosecond time-resolution of the temporal response. The THz-TDS system used in this work is based on a Ti:sapphire laser (Femtolasers, Fusion) with 75 MHz repetition rate. The output pulses at around 800 nm wavelength have a length of about 20 fs. The output beam is split in two parts to generate and detect the THz probe pulse. The THz pulse is generated via a photoconductive antenna (TeraSED, Gigaoptics). The THz field is linearly polarized. The transmission of the THz pulse through the sample is measured in the detection arm via electro-optic sampling in a ZnTe crystal followed by a quarter wave plate, a Wollaston prism and a pair of balanced silicon photodetectors. THz transients are recorded point by point using a delay stage between the THz beam and a sampling beam using lock-in detection with an integration time of 300 ms. Transmission spectra are obtained through Fourier transformation of the THz transient.

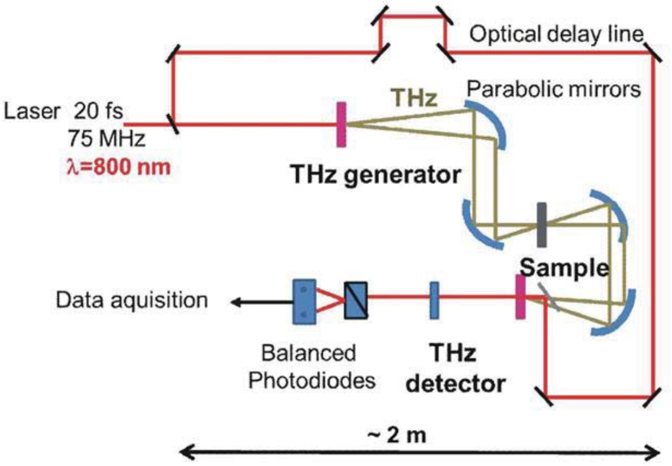

Fig. 2. Schematic of the THZ-TDS setup.

III. PLASMONIC FIELD ENHANCEMENT CARRIER SUBSTRATE

It has been shown recently that plasmonic structures can significantly enhance the sensitivity of detection of THz spectrometers, e.g. detection of thin layers of inorganic or biological material [7-9]. The plasmonic substrates used in this work were composed of silicon-based THz bowtie antennas, where two triangles of conductive material with facing apices are separated by a small gap. For incident radiation polarized along the longitudinal axis of the antenna it is possible to excite Localized Surface Plasmon Polaritons (LSPP), which leads to a peak in the extinction spectrum, as well as a large local field enhancement in the gap of the antenna. Such field enhancements in highly subwavelength areas are particularly interesting for sensing and spectroscopy of small volumes where the interaction between the radiation and the substance to detect is greatly enhanced. At THz frequencies the field decay of the evanescent tail of a LSPP is typically a few micrometers. THz plasmonics is hence a powerful candidate for enhanced ultra-thin layer detection. The fabrication process started from commercially available quartz (fused silica) 6” wafers, and implanted Silicon-on-Insulator (SOI) wafers. The two wafers were bound together using a benzocyclobutene (BCB) based process. After wet etching of the silicon substrate

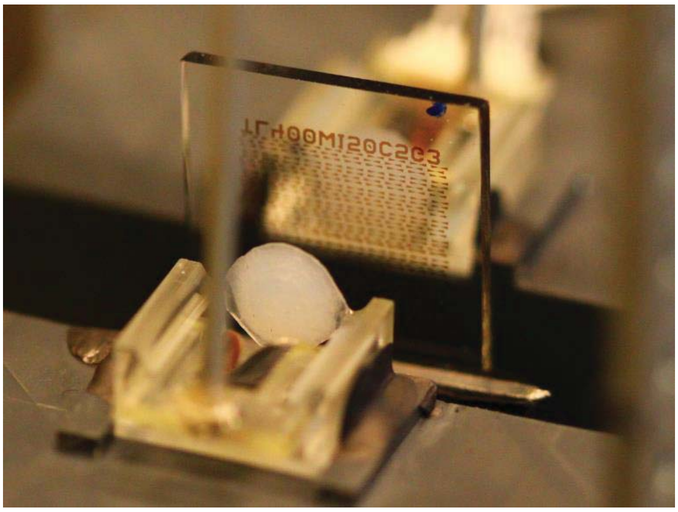

Fig. 3. Configuration of the all-electronic set up to measure the transmission through a plasmonic surface. The plasmonic chip is made of a collection of bowtie antennas.

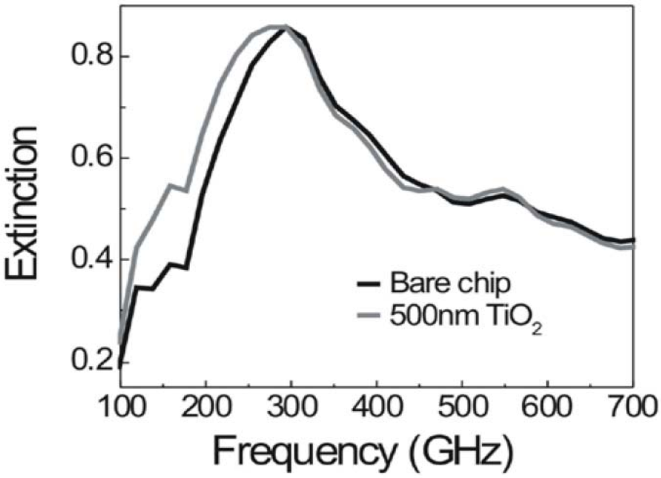

Fig. 4 Measured extinction using THz time domain spectroscopy. The extinctions of a bare plasmonic chip with that of a similar chip covered by a 500 nm TiO2 layer are compared.

and the silica buffering layer, a 1.5 μm thick doped silicon layer remained on top of the quartz wafer. Bowtie antenna patterns were subsequently defined by conventional optical lithography and dry etching using the photoresist as etch mask. An example of a *plasmonic chip,* i.e., a quartz substrate of 1x1 cm^2 onto which a collection of silicon bowtie antennas have been etched, is shown in Fig. 3 in the measurement configuration with the all-electronic spectrometer. The layers to be sensed were deposited on top of the plasmonic chips. The dimensions of the resonant bowtie antennas are defined by the base and height of the triangles, being these 150 μm and 395 μm and the antenna gap G=5 μm. Fig. 3b shows a photograph of a plasmonic surface in the beam path of the all-electronic spectrometer.

IV. MEASUREMENT RESULTS

In order to evaluate the potential of the THz all-electronic instrument as a spectrometer capable of detecting ultra-thin films, we deposited a 500 nm layer of titanium oxide (TiO_2) on top of the plasmonic chip by plasma enhanced chemical vapor deposition (PECVD). The deposition of the TiO_2 layer is conformal to the shape of the antennas. The deposited layer can be considered ultra-thin (ratio of the layer thickness to the operating wavelength at 200 GHz is 1/3000).

Fig. 4 displays the extinction spectrum of a plasmonic chip measured with the THz TDS system. The TDS spectra are obtained in the time domain by measuring consecutively four THz pulses and averaging them in order to reduce the noise level. We can see that the resonance peak of the bowtie antennas shifts to lower frequencies when the dielectric layer is added on the top of the plasmonic chip. The shift to lower energies (red-shift) of the resonance peak is due to the reduction of restoring force of the oscillating charges caused by the depolarization field induced by the high refractive index TiO2 layer. This effect is combined to the depolarization field across the effective gap of the antenna. Ref. [10] shows that smaller gap sizes induce a red-shift of the antenna resonance.

Fig. 5 presents a comparison of the extinction spectra of a plasmonic chip with and without a TiO_2 layer, measured (a) with the TDS setup and (b) with the all-electronic instrument. We note that in the measurement range only the lower frequency side of the plasmonic resonance (extinction peak) is measured. The THz extinction spectrum of the plasmonic chip is defined by $E=1-T_{sample}/T_{ref}$, where E is the extinction of the sample and T_{sample} the transmission through the sample, and T_{ref} the transmission through a reference. The reference sample is a quartz substrate of equal thickness to that of the plasmonic chip. In the range of measured frequencies the presence of the dielectric layer induces an increase of the extinction due to a

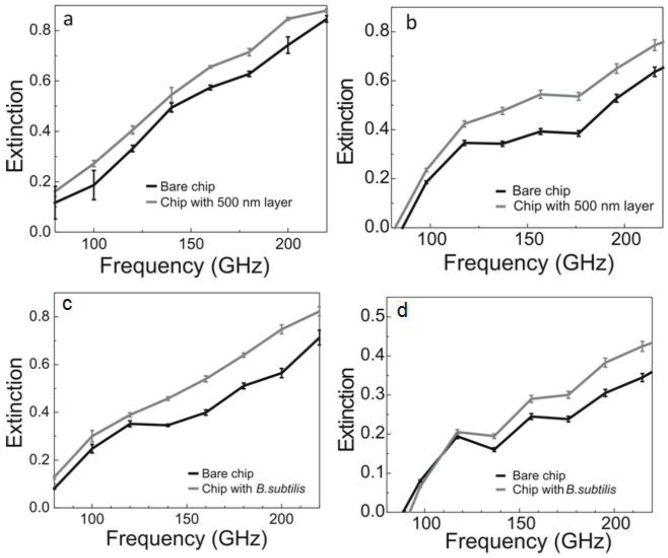

Fig. 5. Averaged measured extinction spectra of a plasmonic chip with and without a thin TiO_2 or bacterial layer with a conventional THz-TDS (left) and the all-electronic spectrometer (right).

shift of the resonance to lower frequencies, similarly seen with both instruments. In particular it is possible to detect an inorganic layer with thickness to wavelength ratio of 1/3000. Individual differences in the shape of the extinction spectrum of the plasmonic chip measured with the two setups are probably due to differences in beam shape and illumination (different distribution of wavevectors) at the surface of the sample. Chip to chip fluctuations explain the small differences in extinction between the different plasmonic chips used in this work. It is interesting to note that the detection capability of the all-electronic THz instrument is similar to that of the TDS systems. As a next step, the detection sensitivity for a bacterial layer is investigated. We deposit a thin layer of *B. subtilis* bacteria (layer thickness of a few μm) on top of a second plasmonic chip. Fig. 5 c and d compares the extinction of the plasmonic chip with and without the bacterial layer, for both THz spectrometers. The variation of the extinction spectrum due to the layers as measured with both setups is in good qualitative agreement. Similarly, the presence of the bacterial layer shifts the extinction spectrum to lower frequencies with a magnitude which is comparable in bth measurements. From these results we can conclude thatthe all-electronic instrument has the capability to perform in a similar range of sensitivities to that of a conventional THz-TDS setup. However, the TDS setup has a broader bandwidth and is more sensitive at higher frequencies while the all-electronic system is more compact and can in principle be produced at low cost and in high volumes.

V. CONCLUSION

The operation of an ultra-broadband electronic THz spectrometer, combined with a sensitivity enhancing plasmonic sample carrier substrate, is demonstrated for the first time. Moreover, a comparison between the performances of the all-electronic THz spectrometer with a conventional THz time domain spectrometer has been presented in the context of thin film sensing. It was demonstrated that the detection of deep subwavelength inorganic and bacterial layers on top of a plasmonic chip was possible with the all-electronic THz instrument in a similar fashion to that obtained with the conventional THz-TDS spectrometer. The equivalent response of both setups spans over the range of operation of the THz all-electronic instrument (20 to 220 GHz). An operation range above 220 GHz is expected for next generation devices. This shows the strength to combine an all-electronic instrument with plasmonic sensitivity enhancers to perform spectroscopic analyses. Applications for such a versatile device span from medical analyses in a point-of-care environment, to spectroscopy for substance recognition to consumer applications.

VI. ACKNOWLEDGEMENTS

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